The distribution of galaxy morphological types and the morphology-mass relation in different environments at low redshift

Rosa Calvi[1]*, Bianca M. Poggianti[2], Giovanni Fasano[2], Benedetta Vulcani[1,2]

[1]*Astronomical Department, Padova University, Italy*
[2]*INAF-Astronomical Observatory of Padova, Italy*

ABSTRACT

We use ~ 2000 galaxies belonging to different environments to show how the fractions of different galaxy morphological types vary with global environment and as function of galaxy stellar mass at low redshift. Considering mass limited galaxy samples with $log_{10}M_\star/M_\odot \geqslant 10.25$, we find a smooth increase/decline in the fraction of Es-S0s/late type galaxies going from single galaxies, to binaries, to groups. Considering all environments, the fractional variation is more conspicuous for S0s and late-types than for ellipticals solely due to a sharp enhancement/dearth of S0s/late-types in clusters compared to other environments. The morphological distribution of galaxies in the mass range $10.25 < log_{10}M_\star/M_\odot < 11$ is rather independent both of galaxy stellar mass and global environment, except in clusters. The morphologies of galaxies more massive than $log_{10}M_\star/M_\odot = 11$ are instead a function of both galaxy mass and global environment. The morphology-mass relation therefore changes with global environment, showing that galaxy stellar mass cannot be the only parameter driving the morphological distribution of galaxies. The morphology-mass relations for S0 and late-type galaxies in clusters are peculiar compared to other environments, and this strongly suggests that cluster-specific effects act on these two types of galaxies, and that a significant number of S0s in clusters has a different origin with respect to S0s in other environments.

Key words: galaxies: formation: general – galaxies: morphologies – galaxies: groups – galaxies: clusters – galaxies: binary systems – galaxies: isolated galaxies – galaxies: morphology-mass relation

1 INTRODUCTION

Morphology is one of the key observables in extragalactic astronomy for understanding the formation and evolution of galaxies, and it is the consequence of all physical processes at work.

The origin of such processes can be both external (environmental) or internal (intrinsic) to the galaxy itself. The strongest evidence of a correlation between the morphological types (Hubble types) and the environment in which galaxies are located comes from studies conducted on galaxy clusters. The well-known morphology-density relation, first described by Dressler (1980a,b) shows that ellipticals and S0s are the dominant population in high density regions while galaxies in low density regions are mainly spirals. A relation between galaxy morphologies, or structural parameters, and local density was found to exist also in galaxy groups by Postman & Geller (1984) and Tran et al. (2001), and in the SDSS general field (Goto et al. 2003; Kauffmann et al. 2004).

Studies of higher redshift clusters proved the existence of a morphological evolution of galaxies (Dressler et al. 1997;

Fasano et al. 2000; Postman et al. 2005) with an increase of the S0 fraction at low redshift at the expense of the spiral population. The morphological evolution depends strongly on galaxy stellar mass both in clusters and in the field (Vulcani et al. 2011; Oesch et al. 2010), and it is stronger in low-mass than in massive clusters (Poggianti et al. 2009; Wilman et al. 2009; Just et al. 2010). Measuring the evolution of galaxy morphologies as a function of environment represents an important step towards a better understanding of the observed morphological mix, and for disentangling between the role of environment and the role of galaxy intrinsic effects. Kauffmann et al. (2003) found that galaxy structure is strongly correlated with galaxy stellar mass. On the other hand, the distribution of galaxy stellar masses itself depends on local density (Baldry et al. 2006; Bolzonella et al. 2010; Vulcani et al. 2011 submitted). Therefore it is hard to assess the relative roles played by the galaxy mass and by the physical processes linked to the environments that the galaxy experienced during its life-time.

To this aim, in the last decade, a great effort has been made to obtain large catalogues of morphologically classified galaxies. For example, detailed morphological classifications have been obtained by Fasano et al. (2006) for cluster galaxies at low redshift in

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* E-mail: email: rosa.calvi@unipd.it

the WIde-field Nearby Galaxy-cluster Survey (WINGS), and several catalogues with visual classifications have been produced for SDSS field galaxies (Nair & Abraham 2010; Baillard et al. 2011; Lintott et al. 2008; Fukugita et al. 2007).

Recently, Bamford et al. (2009), using a local, visually classified sample from the Galaxy Zoo project, analysed the relationship between galaxy morphology, colour, environment and stellar mass characterising the environment by local galaxy density and by distance from the nearest group/cluster with $M = 10^{13} - 10^{15} \, h^{-1} \, M_\odot$. They showed that "only a small part of both the morphology-density and colour-density relations can be attributed to the variation in the stellar-mass function with environment."

In spite of the recent observational progress, what drives the observed trends of the different morphological types remains still a controversial topic not fully explored. For example, to date, there has not been any large statistical study on the morphological distribution of galaxies with *global*, as opposed to local, environment. By galaxy "global environment" we mean the structure to which the galaxy belongs, from massive clusters, to groups, to haloes hosting a single luminous galaxy, over the whole range of galaxy system masses, and corresponding dark matter halo masses.

This letter is the first work which analyses how the morphological mix and the relation between morphological fractions and galaxy stellar mass change in the local Universe not as a function of local galaxy density, but as a function of global environment.[1] To do this we use two galaxy datasets representative of the whole range of cosmic structures: the Padova-Millennium Galaxy and Group Catalogue (PM2GC) of groups, binary systems and isolated galaxies (Calvi et al. 2011a), built from the Millennium Galaxy Catalogue (MGC) (Liske et al. 2003), and the cluster sample from the WINGS survey (Fasano et al. 2006).

The higher quality imaging of the MGC and WINGS surveys compared to the Sloan survey and the combination of multiwavelength photometry and spectroscopy for both our samples allow us to give a clear representation of the morphological distribution of galaxies in different environments as a function of galaxy stellar mass. We adopt $H_0 = 70 \, \mathrm{km \, Mpc^{-1} s^{-1}}$, $h = H_0/100$, $\Omega_m = 0.3$ and $\Omega_\lambda = 0.7$.

2   THE DATASETS

The data used in this letter consist of two samples of galaxies in the local Universe, in which we identify different environments.

We selected group, binary, isolated and general field galaxies from the PM2GC (Calvi et al. 2011a), a sample sourced from the MGC (Liske et al. 2003; Driver et al. 2005). The MGC is a B-band contiguous survey of $\sim 38 \deg^2$, complemented by a highly complete spectroscopic survey down to B=20. The PM2GC is based on the spectroscopically complete sample including all galaxies in the MGC area in the redshift range $0.03 \leqslant z \leqslant 0.11$ brighter than $M_B < -18.7$.

The PM2GC catalogue of groups (PM2-G) contains 176 galaxy groups at $0.04 \leqslant z \leqslant 0.1$ with at least three members brighter than $M_B = -18.7$, identified using a FoF group-finding algorithm. A galaxy is a group member if its spectroscopic redshift lies within $\pm 3\sigma$ from the median group redshift and if it is located within a projected distance of $\leqslant 1.5 \, R_{200}$[2] from the group geometrical centre. Galaxies which have no neighbour or solely one with a projected mutual distance $\leqslant 0.5 h^{-1} \mathrm{Mpc}$ and a redshift within $1500 \mathrm{km \, s^{-1}}$ are considered "isolated" galaxies (PM2-FS) or "binary-system" galaxies (PM2-FB), respectively. The general field (PM2-GF) includes all galaxies regardless of environment, and assembles galaxies in the PM2-G, PM2-FS and PM2-FB together with galaxies that, although located in a trial group, did not make it into the final group sample. A detailed description of the FoF method and catalogues of PM2GC groups and galaxies in different environments can be found in Calvi et al. (2011a).

For the analysis conducted in this letter we prune the PM2GC catalogues of isolated, binary system and general field galaxies to the same redshift range of groups, thus $0.04 \leqslant z \leqslant 0.1$.

In addition, we use a sample of galaxies belonging to 21 clusters taken from WIde-Field Nearby Galaxy-cluster Survey (WINGS) [3], a multiwavelength survey based on deep optical (B,V) wide field images of 77 clusters at $0.04 < z < 0.07$ selected in the X-ray (Fasano et al. 2006) which span a wide range in velocity dispersion (σ typically between 500-1100 km s^{-1}) and X-ray luminosity (L_X between 0.2-$5 \times 10^{44} \mathrm{ergs^{-1}}$). The galaxy spectroscopic completeness of this subsample of clusters is $\geqslant 50\%$, and a spectroscopic incompleteness correction has been applied to our analysis. For redshifts measurements, cluster membership and completeness see Cava et al. (2009).

Although reliable estimates of individual halo masses are available only for WINGS structures based on cluster velocity dispersions and X-ray luminosity, by combining PM2GC and WINGS certainly we are statistically investigating a very broad range of global environments, and corresponding dark matter halo masses, from $\sim 10^{15} M_\odot$ for WINGS, to the order of $\sim 10^{12} M_\odot$ or lower for single galaxies.

For all galaxies in PM2GC and WINGS, stellar masses have been estimated using the Bell & de Jong (2001) relation which correlates the stellar mass-to-light ratio (M/L) with the optical colors of the integrated stellar populations[4]. Our mass estimates are in agreement with DR7 masses and with estimates obtained from the spectrophotometric model fitting of WINGS spectra, with a scatter that is equal to the typical error on photometric mass estimates (0.2-0.3dex), without any dependence on morphological type (see Calvi et al. 2011 for PM2GC, and Vulcani et al. 2011 and Fritz et al. 2011 for WINGS for all details regarding stellar masses). In order to properly investigate the relation between morphology, galaxy mass and environment, without being affected by the different distributions of star formation histories (hence colors) in different environments, it is important to restrict the analysis to a galaxy sample that is complete in mass. The PM2GC galaxy stellar mass completeness limit was computed as the mass of the reddest M_B=-18,7 galaxy ($B-V$=0.9) at our redshift upper limit (z=0.1), and it is equal to $M_\star = 10^{10.25} M_\odot$. The WINGS sample is complete in mass down to $M_\star = 10^{9.8} M_\odot$, but for the purposes of this work, we have adopted for WINGS the same galaxy mass limit as for the PM2GC.

Hence, all the results presented in this paper are based on galaxy stellar mass limited samples ($M_\star \geqslant 10^{10.25} M_\odot$), for a

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[1] See also Wilman & Erwin (2011) submitted, Dave Wilman 2011 private communication.

[2] $R_{200} = 1.73 \frac{\sigma}{1000 \, \mathrm{km \, s^{-1}}} \frac{1}{\sqrt{\Omega_\Lambda + \Omega_0 (1+z)^3}} \, h^{-1} \, \mathrm{Mpc}$

[3] http://web.oapd.inaf.it/wings

[4] The relation is: $\log_{10}(M_\star/L_B) = a_B + b_B(B-V)$ having considered the B-band photometry, a Bruzual & Charlot model with a_B=-0.51 and b_B=1.45 for a Salpeter IMF (0.1-125 M$_\odot$), subsequently scaled to a Kroupa (2001) IMF, and solar metallicity.

Envir.	N. of gal.	Galaxy type			
		Ellipticals	S0s	Late-type	Early-type
WINGS	690 (1056.12)	33.8±1.5%	50.7±1.5%	15.4±1.0%	84.5±1.0%
PM2-GF	1188	27.0±1.3%	28.7±1.3%	44.3±1.5%	55.7±1.5%
PM2-G	583	29.7±1.9%	32.4±2.0%	37.9±2.1%	62.1±2.5%
PM2-FB	174	25.3±3.5%	25.8±3.6%	48.8±4.0%	51.1±4.0%
PM2-FS	334	21.5±2.3%	24.2±2.5%	54.2±2.8%	45.7±3.0%

Table 1. Number of galaxies and fractions of each morphological type in the PM2GC and WINGS mass-limited samples with $M_\star = 10^{10.25} M_\odot$. Early-type galaxies comprise ellipticals and S0s. Errors are binomial. The WINGS number of galaxies between brackets is the weighted total number of galaxies above our completeness limit.
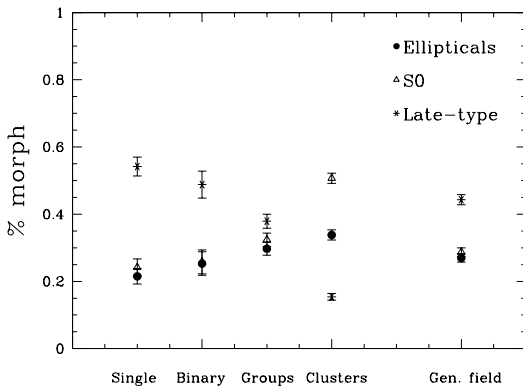

Figure 1. Morphological fractions in different global environments for our mass-limited samples (**for** $log_{10} M_\star / M_\odot \geqslant 10.25$), as in Table 1. Errors are binomial.

Kroupa (2001) IMF. The total numbers of galaxies in each environment above our mass limit are listed in Table 1.

To morphologically classify galaxies in both samples we used MORPHOT, an automatic tool purposely designed (Fasano et al. 2011 in press), see also Appendix A in Fasano et al. (2010), which used B-band images for PM2GC galaxies and V-band images for WINGS. Visual inspection of a random subset of 300 galaxies showed no significant systematic shift in broad morphological classification (E, S0 or late-type) and a typical scatter (ΔT=1.2) between the V and B WINGS images. By adding to the classical CAS (Concentration/Asimmetry/clumpinesS) parameters a set of additional indicators derived from digital imaging of galaxies, this tool mimics the visual classifications. The MORPHOT morphological classifications have been proved to be as effective as the eyeball estimates, as shown by the comparison with visual classifications of WINGS and SDSS images yielding an average difference in Hubble type ΔT ($\leqslant 0.4$) and scatter ($\leqslant 1.7$) comparable to those among visual classifications of different experienced classifiers (see Fasano et al. 2011). In particular, MORPHOT has been shown to be able to distinguish between ellipticals and S0 galaxies with unprecedented accuracy.

3 RESULTS

3.1 The Hubble type fractions

In Table 1 and Figure 1 we show the morphological fractions for the PM2GC and WINGS mass-limited samples for galaxies with $log_{10} M_\star / M_\odot \geqslant 10.25$.

The fractions of ellipticals, S0s and early-type galaxies (E's + S0's) progressively increase in more massive environments, from single galaxies to binary systems, to groups and clusters. Late-type galaxies follow the opposite trend with global environment.

We note that elliptical galaxies have the smallest fractional variation with environment. Their fraction in clusters ($\sim$34%) is not very dissimilar from that in the general field ($\sim$27%) . For isolated galaxies, binary systems and groups, although the trend is slowly increasing as we move towards more massive environments, the fraction of ellipticals is always between $\sim$22-30%.

The fraction of S0s is very similar to the elliptical fraction in all environments ($\sim$1:1 number ratio) except in clusters (1.5). The S0 fraction ranges from 24% among single galaxies, to 32% in groups, with a jump to 50% in clusters. S0's in clusters are almost twice more common than in the general field.

As a consequence, the early-type fraction ranges from 46% among single galaxies to 85% in clusters. It is striking that even in the least massive environments we consider, (those of single galaxies), almost half of the total galaxy population above our mass limit is composed of early-type galaxies.

Correspondingly, the fraction of late-type galaxies changes strongly with environment. For PM2-FS and PM2-FB this fraction is about $\sim$50%, it decreases for group galaxies to $\sim$38%, and then it declines sharply in clusters (mirroring the S0 cluster enhancement) reaching a fraction of $\sim$15%, a third with respect to the general field ($\sim$44%).

In Poggianti et al. (2009)[5] we found that in clusters ($\sigma > 500\,\mathrm{km\,s^{-1}}$) there is no correlation between the fractions of late-types, S0s and ellipticals and cluster velocity dispersion or X-ray luminosity (both of which are cluster mass proxies), except for a weak anticorrelation of the late-type fraction with X-ray luminosity. Together with the results of this paper, this suggests that the morphological trends we observe going from less massive (single galaxies) to more and more massive environments (groups and clusters) must flatten out for the most massive haloes.

In summary, we see a smooth increase/decline in the fraction of Es-S0s/late type galaxies going to more and more massive environments. On top of that, the cluster environment is characterized by a sharp enhancement/dearth of the S0/late-type fractions compared to other environments. For clusters above $500\,\mathrm{km\,s^{-1}}$ the morphological fractions do not depend on halo mass anymore. Overall, the fraction of elliptical galaxies represents always at least 20% of the galaxy population even in the least massive environments, and at most 34% in clusters.

3.2 The Morphology-Mass relation in different environments

In this section we investigate the dependence of the distribution of morphological types on galaxy stellar mass, and whether this changes with global environment. Table 2 lists the fractions of each morphological type at masses $10.25 \leqslant log_{10} M_\star / M_\odot < 11.0$ and $log_{10} M_\star / M_\odot \geqslant 11.0$ in different environments and can be used in the following to compare the morphological fractions at low- and high-masses, and in different environments in the same mass range.

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[5] In the 2009 work the analysis was carried out for a magnitude-limited sample of galaxies. We have verified that the results do not change for the mass-limited WINGS sample we use in this paper.

% morph.type	WINGS	PM2GC-GF	PM2GC-G	PM2GC-FB	PM2GC-FS
ell $M \geqslant 10^{11} M_\odot$	63.2±4.4%	42.0±4.5%	48.2±4.5%	29.4±13.5%	26.6±9.6%
ell $M < 10^{11} M_\odot$	29.3±1.6%	24.8±1.5%	26.6±2.0%	24.8±3.7%	21.0±2.5%
s0 $M \geqslant 10^{11} M_\odot$	26.3±4.0%	20.0±3.5%	21.6±5.0%	29.4±13.5%	13.3±7.8%
s0 $M < 10^{11} M_\odot$	54.4±1.7%	30.0±1.5%	34.2±2.0%	25.4±3.8%	25.3±2.6%
lt $M \geqslant 10^{11} M_\odot$	10.4±2.9%	38.0±4.5%	30.1±6.0%	41.1±14.3%	60.0±10.4%
lt $M < 10^{11} M_\odot$	16.1±1.2%	45.2±1.5%	39.2±2.5%	49.6±4.3%	53.6±3.0%

Table 2. Fractions of each morphological type above and below $M = 10^{11} M_\odot$ in different environments. Errors are binomial.

3.2.1 Fixed environment

The morphological fractions at masses below and above $\log_{10} M_\star/M_\odot = 11.0$ are different (Table 2). These differences are statistically significant in clusters, groups and general field, while among binaries and single galaxies numbers are too low to draw conclusions.

Figure 2 shows how the fraction of each morphological type varies with stellar mass in the four PM2GC environments and in clusters. We note that, as discussed in detail in Calvi et al. (in prep.), in binary and single systems there are no galaxies with masses $\log_{10} M_\star/M_\odot \geqslant 11.2$ and $\log_{10} M_\star/M_\odot \geqslant 11.55$, respectively, indicating that the most massive galaxies are only present in the most massive haloes. Up to $\log_{10} M_\star/M_\odot \sim 11.1$, in the PM2GC there is generally little dependence of the morphological fractions on galaxy mass. Moreover, at these masses late-type galaxies tend to be the most common type of galaxies in all PM2GC environments, being matched by S0s only in groups.

In contrast, at masses $\log_{10} M_\star/M_\odot > 11.1$, there is a noticeable dependence of the morphological mix on galaxy mass in those environments hosting galaxies this massive. In the PM2-FS the late-type galaxy fraction rises towards higher masses, while in groups it declines, as the most massive group galaxies are mostly ellipticals.

In clusters, from Vulcani et al. (2011), the trends partly resemble those in the PM2GC groups, except that in clusters the dominance of ellipticals at high masses is even more pronounced and for $\log_{10} M_\star/M_\odot > 10.8$ there is a clear declining trend of S0s with galaxy mass that is absent in groups. This behaviour of the S0 fraction-galaxy mass relation in clusters is different from all other environments, where the S0 fraction remains rather constant at all galaxy masses.

Though it is commonly believed that the morphological mix depends on galaxy mass, our results highlight that such a dependence is generally weak at masses in the range $\log_{10} M_\star/M_\odot = 10.25 - 11$, while it becomes strong at higher masses, where the dominant galaxy type changes with global environment (elliptical in clusters and groups, late-type among single galaxies).

3.2.2 Fixed morphological type

Figure 3 comprises all environments, and directly shows the strong environmental variation of the morphology-mass relation for each galaxy type. The upper panels present the differential fractions, and the lower panels the cumulative distributions showing the fractions for galaxies more massive than a mass M. Comparing our general field with results obtained using the Nair & Abraham (2010) catalogue at the redshifts of our work, we find qualitatively similar morphological trends with mass, though even steeper high-mass slopes for ellipticals and late-types.

The top panels in the figure highlight that the variation of the morphology-mass relation *with environment* is pronounced (1)
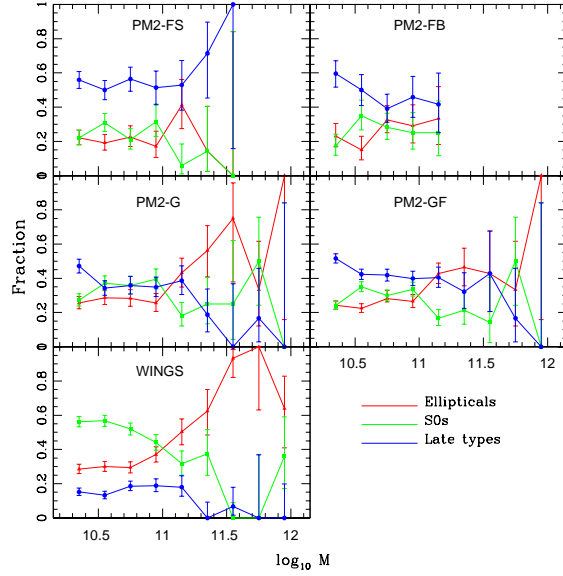

Figure 2. The fraction of each morphological type as a function of stellar mass in different environments: PM2 single-field (top left), PM2 binary-field (top right), PM2 galaxy groups (middle left), PM2 general field (middle right), WINGS (bottom left, reproduced from Fig.10 of Vulcani et al. 2011). The WINGS number of galaxies is weighted on the total number of galaxies above our completeness limit. Errors are binomial.
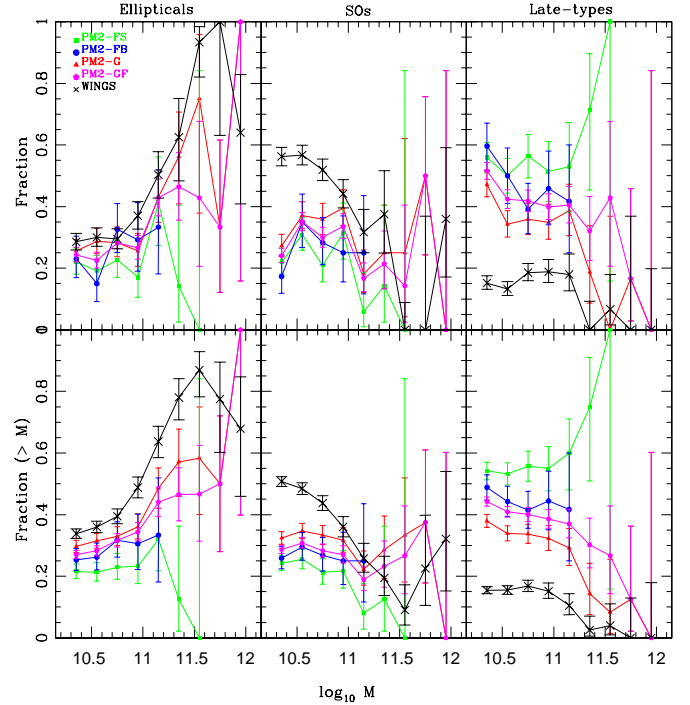

Figure 3. Top. The fractions of elliptical (left panel), S0 (central panel) and late-type (right panel) galaxies in different environments as a function of stellar mass. **Bottom.** Cumulative distributions of ellipticals, S0s and late-type galaxies: fractions of each type among galaxies more massive than $\log_{10} M$ on the X axis. This plot can used to infer the global morphological fractions in mass-limited samples for any mass limit higher than ours. Errors are binomial. (The WINGS galaxies are weighted on the total number of galaxies above our completeness limit.)

above all at high galaxy masses ($log_{10}M_\star/M_\odot > 11$), but also (2) at low galaxy masses for S0 and late-type galaxies in clusters compared to the other environments.

(1) In non-cluster environments, the fraction of each morphological type at masses $10.25 < log_{10}M_\star/M_\odot < 11$ changes relatively little from one environment to the other, while it varies much more strongly with environment for $log_{10}M_\star/M_\odot > 11$ (also Table 2). The environmental variation at high masses is especially outstanding for ellipticals and for late-types.

(2) The peculiarity of the behaviour of the S0 and late-type fractions in clusters suggests cluster-specific effects on these two types of galaxies. It also suggests that a significant number of S0 galaxies in clusters has a different origin with respect to S0s in other environments. The S0 fraction-galaxy mass relation in clusters resembles more closely the late-type fraction-mass relation in the general field and groups than the S0-mass relation in non-cluster environments, in agreement with a scenario in which clusters are very efficient in transforming spiral galaxies into (some of today's) S0s (Dressler et al. 1997; Fasano et al. 2000). We speculate that while a large number of cluster S0s have a "late-type origin", a large number of non-cluster S0s have a truly "early-type origin" (a dominant spheroidal component that forms a very small disk, an "intermediate type" between disky ellipticals and Sa's).

The fact that the morphology-mass relation changes significantly with environment demonstrates that galaxy mass is not the only parameter driving the morphological distribution of galaxies. Thus, the change of morphological mix with global environment cannot be solely due to an eventual change in the galaxy mass function with halo mass (see Calvi et al. in prep. for a description of the galaxy mass function as a function of global environment).

4 SUMMARY

We use group, binary and isolated field galaxies from the PM2GC sample and cluster galaxies from the WINGS survey to study the morphological fractions and morphology-mass relation in different environments for mass-limited galaxy samples with $log_{10}M_\star/M_\odot \geqslant 10.25$. Morphologies were derived from B-band and V-band images in PM2GC and WINGS, respectively, with our tests showing no systematic shift in broad morphological classification between B and V.

- We observe a smooth increase/decline in the fraction of Es-S0s/late type galaxies going from single galaxies, to binaries, to groups. Considering all environments, the fractional variation is more conspicuous for S0s and late-types than for ellipticals, due to a sharp enhancement/dearth of S0s/late-types in clusters compared to other environments. Poggianti et al. (2009) found that above $500\,\mathrm{km\,s^{-1}}$ the morphological fractions do not depend on halo mass anymore.
- In all environments the morphological fractions strongly depend on galaxy stellar mass *only* for masses above $log_{10}M_\star/M_\odot \sim 11$ (10.8 in clusters), while they are weakly dependent of mass at $10.25 < log_{10}M_\star/M_\odot < 11$. At high galaxy masses, the dominant type changes with global environment (elliptical in clusters and groups, late-type in single galaxies).
- Also the variation of the morphology-mass relation with environment is much more pronounced at $log_{10}M_\star/M_\odot > 11$, especially for ellipticals and late-types, while at lower masses there is relatively little change from one environment to the other, except for clusters.

- The morphology-mass relations for cluster S0s and late-types remarkably differ from the corresponding relations in all other environments. Our findings strongly suggest that cluster-specific effects act on these two types of galaxies, and that a significant number of S0s in clusters has a different origin with respect to S0s in other environments.

Our results show that the morphology-mass relation changes with global environment and that galaxy stellar mass cannot be the only parameter driving the morphological distribution of galaxies.

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